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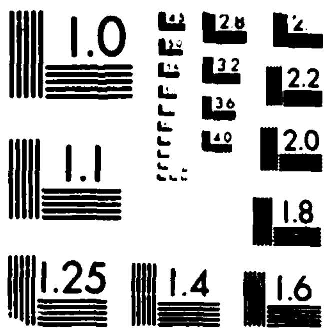

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NRL Memorandum Report 6129

Development of Inductive Storage Pulsed Power Generators

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April 6, 1988

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A pulse generator, Pawn, has been assembled at the Naval Research Laboratory. It employees inductive energy storage and opening switch power conditioning techniques with high energy density capacitors as the primary energy store. The capacitor bank stores 1 MJ at 44 kV. The energy stored in the capacitor bank is transferred to a vacuum storage inductor in 20 μs. Wire fuses provide the first stage of pulse compression. Further pulse compression is obtained from a plasma erosion opening switch.

Initial results are encouraging. Nearly 0.1 TW of electrical power was delivered to an electron-beam diode load in a 100-ns FWHM pulse. A peak voltage at the load of $\approx$ 350 kV represents a factor of $\approx$ 14 voltage gain over the initial, 25-kV bank voltage.

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ABSTRACT

A pulse generator, Pawn, has been assembled at the Naval Research Laboratory. It employs inductive energy storage and opening switch power conditioning techniques together with high energy density capacitors as the primary energy store. The capacitor bank stores 1 MJ at 44 kV. The energy stored in the capacitor bank is transferred to a vacuum storage inductor in 20 us. Wire fuses provide the first stage of pulse compression. Further pulse compression is obtained from a plasma erosion opening switch.

Initial results are encouraging. Nearly 0.1 TW of electrical power was delivered to an electron-beam diode load in a 100-ns FWHM pulse. A peak voltage at the load of ≈ 350 kV represents a factor of ≈ 14 voltage gain over the initial, 25-kV bank voltage.

I. Introduction

Inductive energy storage in combination with opening switch power conditioning techniques offers several attractive features for pulsed power applications when compared with conventional, capacitive technology /1-3/. These advantages include compactness and low cost of the primary energy store. Also, because the voltage is high only during the last stages of the power conditioning sequence, some complexities associated with high voltage, such as oil insulated Marx banks, water filled pulse forming lines, and power limiting interfaces, are eliminated. The technical difficulty has always been obtaining the required power conditioning for practical, pulsed power applications, i.e., obtaining > 1-TW, < 100-ns pulses. With inductive storage, the power conditioning must be accomplished by a sequence of opening switches electrically in parallel with each other and the load. Each successive switch opens faster, resulting in higher and higher voltage. The challenge is to understand the physics governing the opening switch behavior well enough to design a system for which the interaction between the system components produces the desired power pulse.

An experimental, inductive storage, pulsed power generator, "Pawn" /4-5/, has been assembled at the Naval Research Laboratory (NRL) using a newly developed low voltage, compact capacitor bank /6/ as the primary store (1 MJ at 44 kV). The nominal 20-us current pulse available from the discharge of this bank energizes the vacuum storage inductance. Wire fuses /1,3-5,7/ provide the first stage of pulse compression. Further pulse compression is obtained from a plasma erosion opening switch (PEOS) /8-11/.

Preliminary results are encouraging. Nearly 0.1 TW of electrical power was delivered to an electron-beam (e-beam) diode load in a pulse of 100-ns full width at half maximum (FWHM). A factor of ≈ 14 voltage gain over the initial, 25-kV bank voltage was achieved.

In Sec. II a description of the Pawn device and a discussion of its electrical operation are presented. Results demonstrating the fuse performance are discussed in Sec. III. In Sec. IV, preliminary, non-optimized results in which a fuse driven PEOS was coupled to an e-beam diode are reviewed. The work is summarized in Sec. V.

II. System Description

The system components are identified in Fig. 1. The pulse generator comprises a capacitor bank, a vacuum coaxial inductor attached to the capacitor bank via parallel plates, a low voltage vacuum feedthrough (not shown), a fuse array contained within a pressurized gas enclosure, a vacuum flashover closing switch that can be command or self-triggered, a vacuum opening switch (PEOS), and an e-beam diode load. The capacitor bank is divided into four submodels, each containing five, 52-uf capacitors connected in parallel in a low inductance (≈ 70 nH) configuration. At the maximum rated charge voltage of ≈ 44 kV, one capacitor stores ≈ 50 kJ. Each submodel is connected to the common parallel plate transmission line in series with an ≈ 14-mΩ, stainless steel safety resistor and a high energy, pressurized, railgap switch. The coaxial energy storage inductor is made of aluminum tubing with welded flanges and connects to a load coupling "tee." This tee section provides mounting surfaces for connecting two coaxial fuse enclosures and the coaxial output assembly. The assembly as shown in Fig. 1 contains the vacuum flashover switch (VFS), the vacuum opening switch (PEOS), and the e-beam load. The latter two components were replaced by an electrolyic resistor when testing the fuse opening switch stage alone. The diagnostics consisted of a Rogowski coil to measure the capacitor bank current, two $\dot{B}$ probes in the vacuum inductive store region, four $\dot{B}$ probes in the fuse tee vacuum

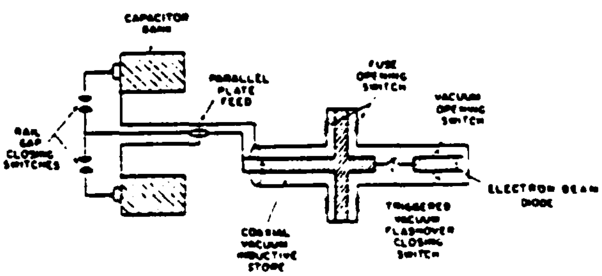

Figure 1. Schematic illustration of Pawn System.

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region (2 for each package), two $\dot{B}$ probes between the VFS and PEOS, four $\dot{B}$ probes on the capacitor side of the PEOS and four $\dot{B}$ probes on the load side of the PEOS. A resistive voltage divider was used to measure the fuse voltage. For experiments with diodes, an inductive voltmeter provided a direct measurement of the load voltage.

A schematic diagram of the equivalent electrical circuit for Pawn is shown in Fig. 2. The total bank capacitance, represented by C, is 1026 μF. The series resistance, R_s = 4.7 mΩ, is made up of R_{BK}, the internal resistance of the capacitors and switches (S_1) and the parallel safety resistors (≈ 3.6 mΩ), plus R_{SKIN}, the skin resistance of the conductors associated with the transmission plate and coaxial inductor. The internal inductance of the bank, L_{BK} includes the switches and transmission plates and is estimated to be ≈ 40 nH. The calculated inductance of the coaxial storage inductor is L_{STORE} = 70 nH. The parallel leg of the circuit represents the fuse assembly with inductance L_F and a variable resistor $R_F(t)$ symbolizing the time-dependent resistance of the fuse. The calculated inductance of a single fuse assembly for a 25-cm long fuse is L_F = 70 nH. This value becomes 35 nH when a second identical fuse assembly is connected at the tee section.

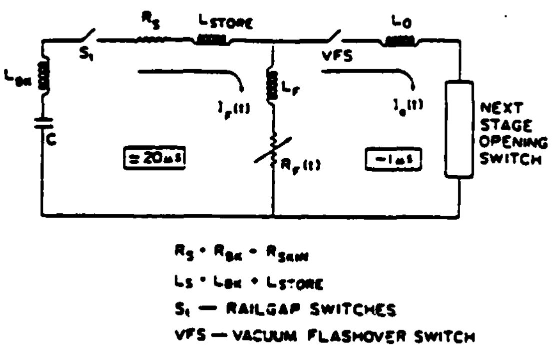

Figure 2. Equivalent circuit for Pawn System.

The capacitor bank is initially charged to a voltage of 20 - 44 kV. When it is discharged by closure of the railgap switches it produces a quasi-sinusoidal pulse of current $I_F(t)$ in the storage inductor and fuse array. Just before the fuse opens the VFS is closed. The voltage pulse resulting from the increasing fuse resistance then transfers current $I_o(t)$ from the fuse into the ouput loop of the circuit. The output loop is shown in the circuit as an inductance L_o in series with an arbitrary element representing a fast opening switch in parallel with a load, or an electrolytic resistor.

III. Characterization of Fuse Operation

The first stage of pulse compression is achieved using wire fuses. Development work for the fuse and fuse package used on Pawn is described elsewhere /4-5/. The fuse is a non-linear resistive circuit element. As more energy is dissipated in the form of joule heating of the fuse wires, the fuse undergoes a phase change from solid to liquid to gas, with an accompanying increase in its resistance. The balance of energy dissipated in the fuse is crucial. Too much dissipated energy drives the fuse into a very low resistance plasma. This may result in a breakdown condition prohibiting any further current transfer or a restrike upon further voltage amplification in the power conditioning sequence. If too little energy is dissipated, the fuse never reaches the highly resistive gaseous state desired for rapid transfer of current. As discussed in several of the references (e.g., 1, 2, 4, 5, 7) for a given time to fuse vaporization there exists a value of the fuse energy density (dissipated energy per unit volume of fuse) for which the required current transfer is achieved. Therefore, the fuse size and system parameters must be matched for optimum performance, i.e., fastest current transfer or, equivalently, highest voltage.

The performance of the capacitor bank and fuse stage with a triggered VFS is illustrated in Fig. 3. These data were obtained with a capacitor bank voltage of 40 kV (800 kJ stored energy), a 43-nH output inductance, and an 11-mΩ electrolytic resistor in place of the next stage opening switch of Fig. 2. Each of the two fuse packages consisted of 86 parallel copper wires, each 50-cm long. The time-dependent load current has a 10-90 risetime of 0.9 μs and peaks at 1.4 MA. This represents a pulse compression ratio (energizing time for inductor with no fuse/risetime of current into load) of ≈ 20. The 200 kV peak fuse voltage represents a voltage gain, defined as the ratio of peak voltage across the fuse to the initial capacitor voltage, of 5.

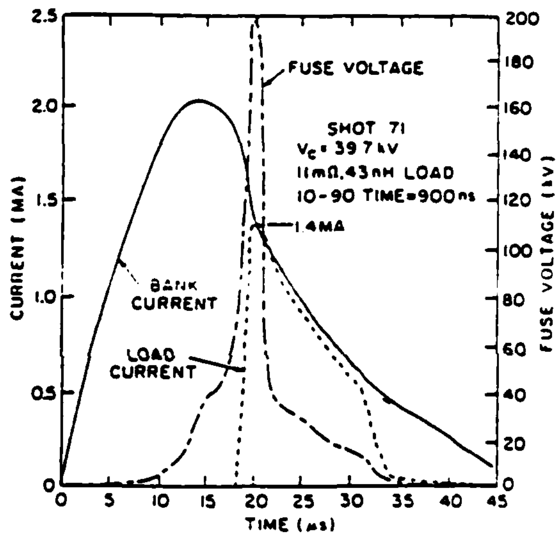

Figure 3. Data obtained at 40 kV charge using an 11-mΩ dummy load and a triggered vacuum flashover output switch.

The excellent fuse reproducibility is illustrated in Fig. 4, which is a six-shot overlay of the measured fuse voltage as a function of time. The standard deviation in peak fuse voltage is < 4% and in time-to-peak is < 1%.

IV. Fuse Driven PEOS Experiment

The PEOS is a fast, high power, vacuum opening switch /8-11/. It consists of plasma sources that inject a flowing plasma through an array of rods into the region between the inner and outer conductors (see Fig. 1) filling the annular region over a limited axial length (≈ 10cm). The plasma sources are fired several microseconds before the VFS is closed so that when the VFS closes the PEOS isolates the e-beam diode from the system. The PEOS must conduct long enough to allow transfer of current out of the fuse stage and then open, generating sufficient voltage to drive electron emission in diode, which is initially an open circuit.

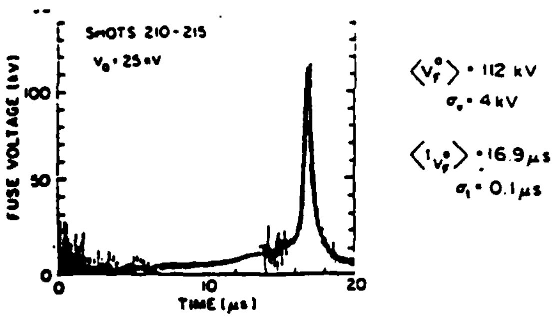

Figure 4. Overlay of six consecutive fuse voltage records illustrating fuse reproducibility.

Detailed operation of the PEOS can be found elsewhere (cf 8-11 and references therein). Briefly, the plasma is injected into the switch region several microseconds before the voltage associated with the fuse is switched to the PEOS cathode via the VFS. As long as the PEOS current remains below a predictable value, which depends on only the plasma parameters and switch geometry, the plasma acts as a good conductor. The conduction occurs through a non-neutral region, called a sheath or gap, at the cathode in a bipolar space-charge-limited fasion /8/ with the electron component emanating from the cathode and the ion component provided by the injected plasma. When the switch current becomes high enough that the bipolar space-charge condition cannot be satisfied by the ions from the injected plasma, the gap widens, providing more ions. This is called the erosion phase. When the switch current increases to the point where the average electron Larmor radius is comparable with the gap size, the electron lifetime in the gap increases and as a result the space-charge condition is modified in such a way that even more ions are required. This is called the enhanced erosion phase and it is during this phase that the gap widens very quickly. A high voltage is generated across the gap and a substantial fraction of current is diverted to the load. The switch is totally open when the magnetic insulation phase is reached. This occurs at a value of current for which the average electron Larmor radius is less than the gap size and all the current reaches the load.

Summarized in Fig. 5 are preliminary results from an experiment in which a fuse driven by the capacitor bank charged to 25 kV transferred current into a PEOS that, in turn, was coupled to an e-beam diode. Plotted as a function of time are the load voltage, V_L, current, I_L power, P_L, and energy, E_L. The zero of time corresponds to the initiation of current in the fuse and the VSF was triggered at $\tau_{SO} = 17.25$ us. Roughly 5 kJ of energy was delivered to the diode in an ≈ 85-ns FWHM pulse. The peak power was ≈ 0.07 TW. Note that the peak diode voltage of ≈ 350 kV (measured directly with an inductive voltmeter) represents a total voltage gain over the initial bank voltage of ≈ 14. This factor results from a gain of ≈ 4 from the fuse and ≈ 3.5 from the PEOS. Filtered, time resolved x-ray diagnostics suggest that the diode voltage thus measured may be an underestimate of the actual voltage. Currently, work is underway directed at improving the system performance by characterizing, understanding, and optimizing the interaction between the fuse and PEOS.

V. Summary

A pulsed power generator employing inductive energy storage and opening switch power

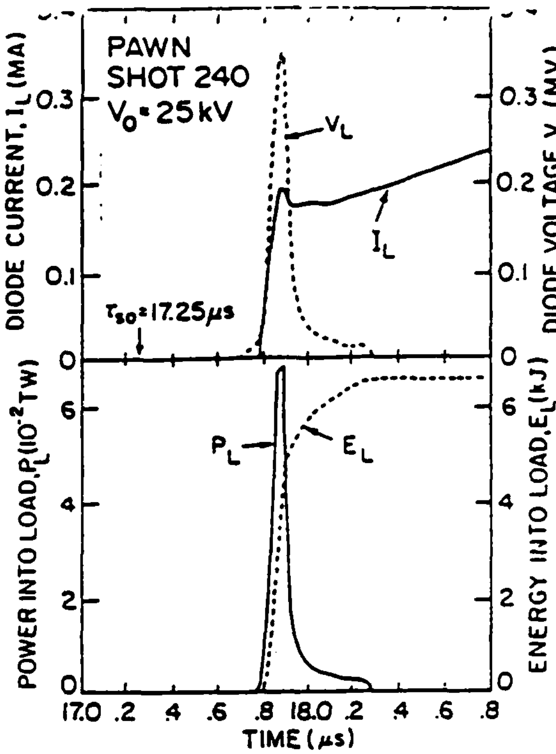

Figure 5. Initial results of experiments using a fuse driven PEOS coupled to an e-beam diode.

conditioning techniques has been assembled at NRL and is now operational. Initial, non-optimized results with the PEOS are encouraging. Nearly 0.1 TW of electrical power is delivered to an electron beam diode in a < 100-ns FWHM pulse. The peak diode voltage is ≈ 350 kV, a factor of ≈ 14 voltage gain over the initial, 25-kV bank voltage. Work is now underway to improve this performance.

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**Sachs/Freeman, Landover, MD.

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